Fast detectors for electron Compton polarimetry

EIC Polarimetry Working Group
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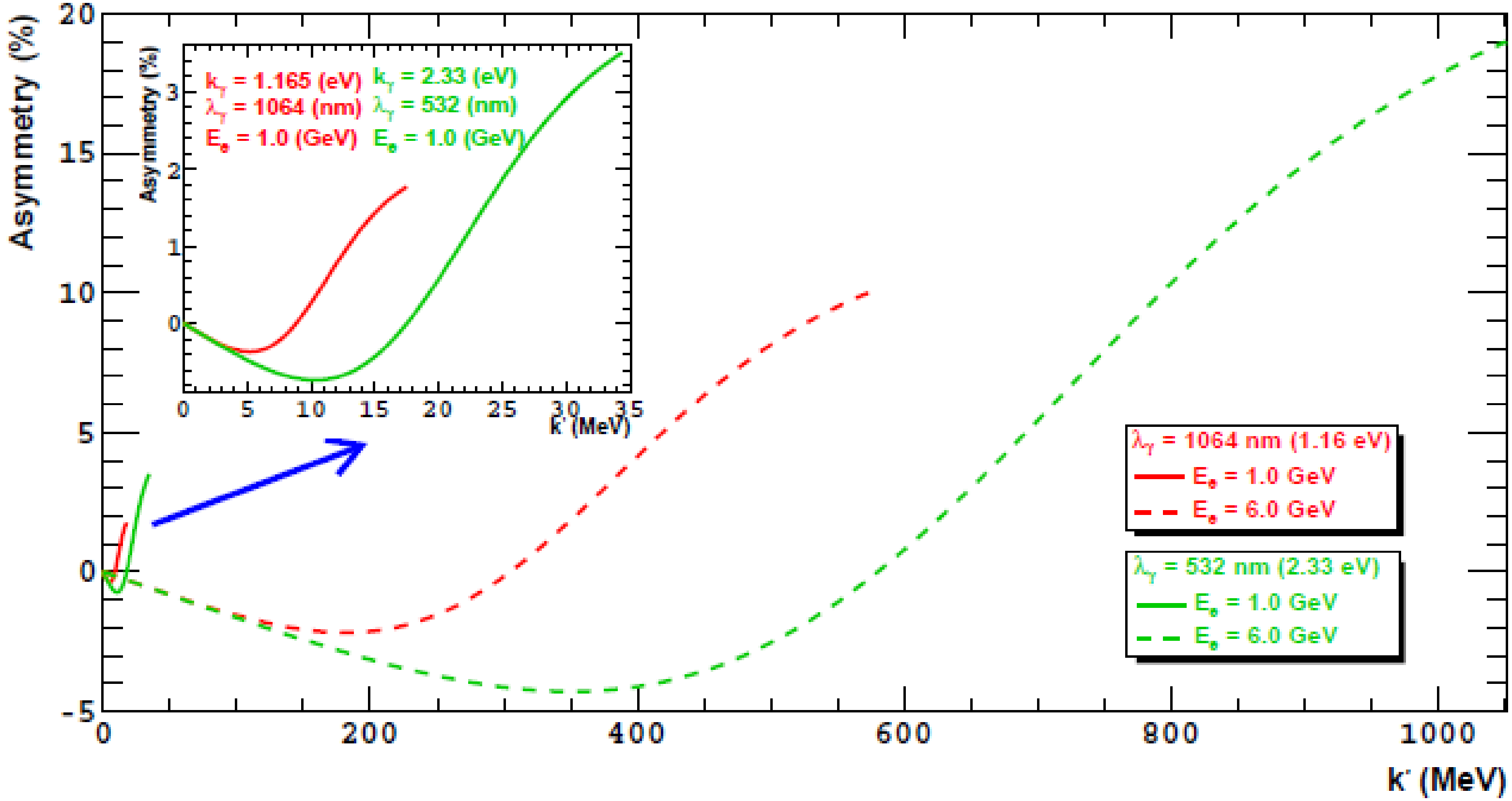
Outline

- Compton overview
- Machine parameters
- Estimated counting rates
- Radiation from Compton signal
- Detectors overview
- TOTEM detector and electronics, tests on diamond and silicon
- MAPS
- Superconducting
- Conclusions

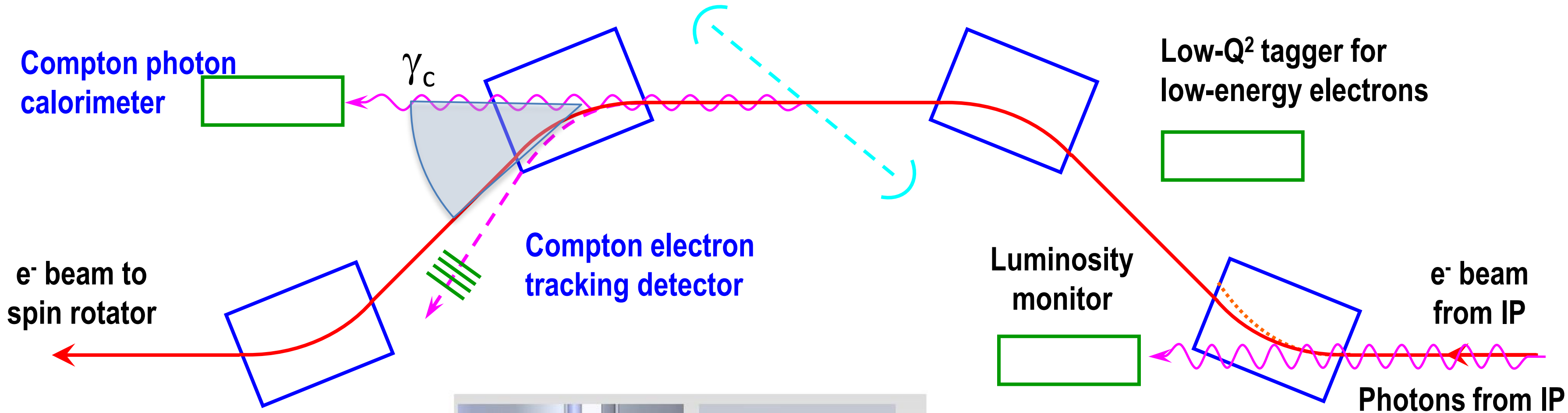
Compton asymmetry

$\sigma(\ \vec{e} + \gamma \longrightarrow e' + \gamma'\ ) \neq \sigma(\ \overleftarrow{e} + \gamma \longrightarrow e' + \gamma'\ )$

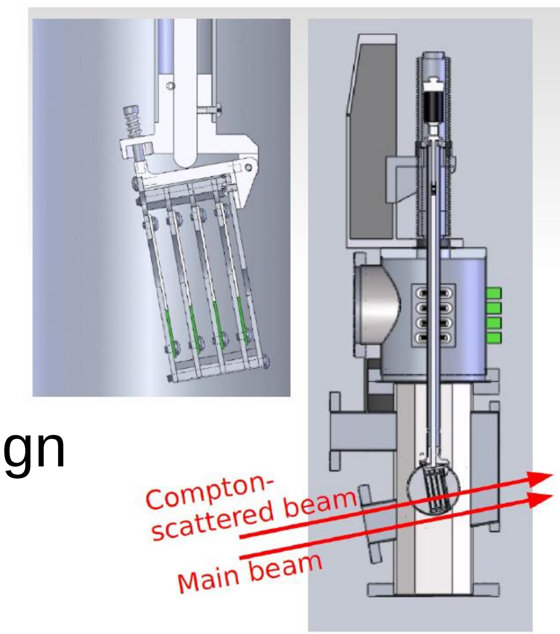
$$\frac{N^{+}-N^{-}}{N^{+}+N^{-}}\left(E_e, k_\gamma, k_{\gamma'}\right) = P_e * A(E_e, k_\gamma, k_{\gamma'})$$



Compton electron detector

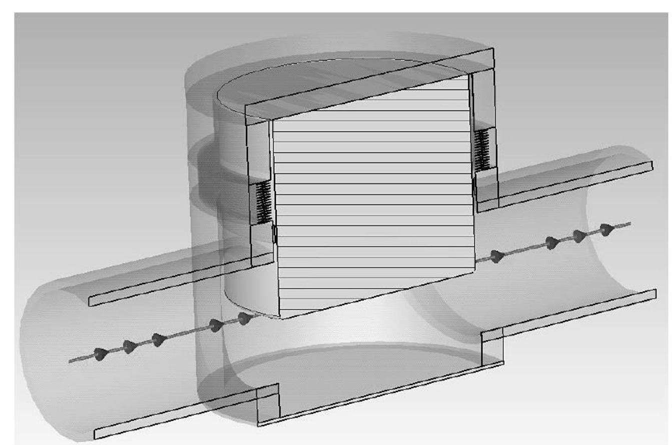


Electron detector not in direct view of synchrotron fan



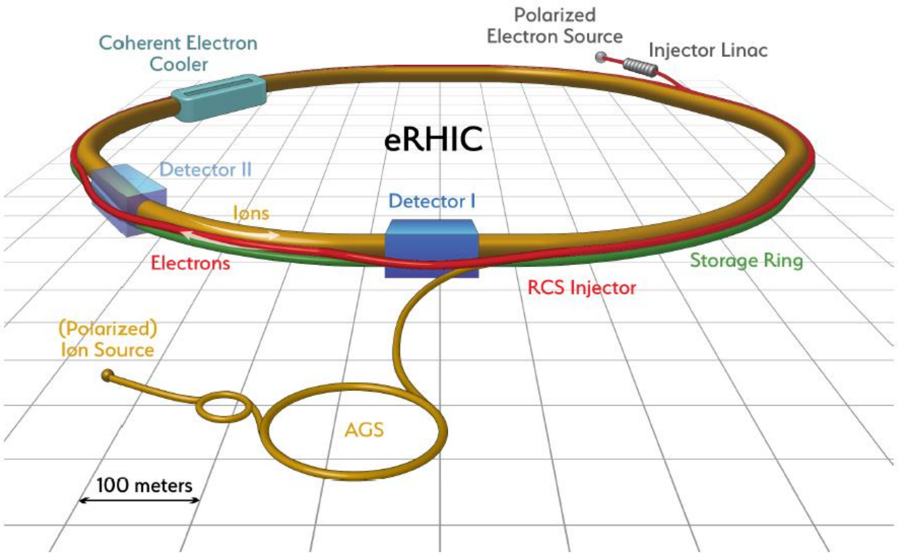
Existing Hall C design

TOTEM Roman Pot



eRHIC

pCDR eRHIC Design Concept



- **Hadron Beam**
  - entirely re-uses injection chain and one of RHIC rings (Yellow ring)
  - partially re-uses components of other ion RHIC ring
- **Electron Accelerator** added inside the existing RHIC tunnel:
  - 5-18 GeV Storage Ring
  - On-energy injector: 18 GeV Rapid Cycling Synchrotron
  - Polarized electron source and 400 MeV injector linac: 10nC, 1 Hz
- **Hadron cooling system** required for $L = 10^{34} cm^{-2} s^{-1}$
  Without cooling the peak luminosity reaches $4.4\ 10^{33} cm^{-2} s^{-1}$

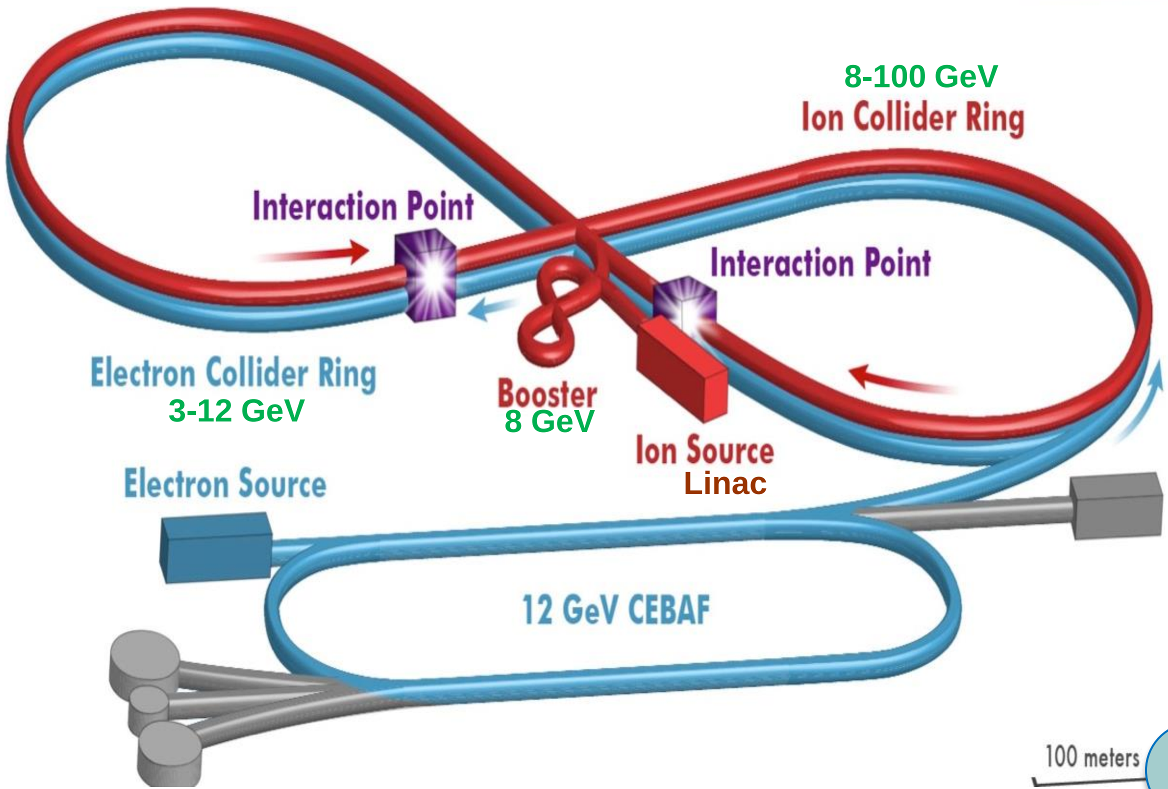
eRHIC beam parameters

Beam Parameters for 275(p)x10(e) GeV

	Nominal Design (with cooling)		Risk Mitigation (no cooling)	
Species	p	e	p	E
Bunch frequency [MHz]	112.6		56.3	
Bunch intensity [10^11]	0.6	1.5	1.05	3.0
Number of bunches	1320		660	
Beam current [A]	1	2.5	0.87	2.5
Rms norm. emit. h/v [um]	2.7/0.38	391/20	4.1/2.5	391/95
Rms emittance h/v [nm]	9.2/1.3	20/1	13.9/8.5	20/4.9
β* h/v [cm]	90/4	42/5	90/5.9	63/10.4
IP rms beam size h/v [um]	91/7.2		112/22.5	
IR rms angular spread h/v [urad]	101/179	219/143	124/380	179/216
b-b parameter (/IP) h/v	0.013/0.007	0.064/0.099	0.015/0.005	0.1/0.083
Rms bunch length [cm]	5	1.9	7	1.9
Rms energy spread, 10^-4	4.6	5.5	6.6	5.5
Max space charge parameter	0.004	neglig.	0.001	neglig.
IBS growth time tr/long, h	2.1/2.0		9.2/10.1	
Polarization, %	80	70	80	70
Hourglass and crab crossing factor	0.87		0.85	
Peak luminosity [10^33 cm-2s-1]	**10.1**		**4.4**	
Integrated luminosity/week, fb^{-1}	**4.51**		**1.12**	

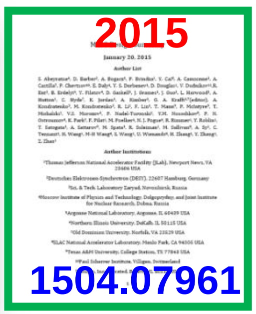
Hadron cooling provides ~factor 4 integrated luminosity increase at E_{CM}=105 GeV. But larger increase, by factor 7-10, is expected in low range of E_{CM} (29-70 GeV).

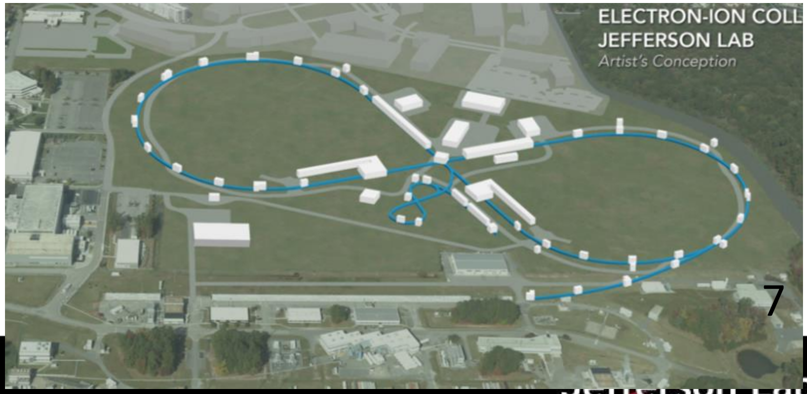
JLEIC Layout: *A Ring-Ring Collider*



- **Electron complex**
  - CEBAF full energy injection
  - Collider ring
- **Ion complex**
  - Ion source/Linac
  - Booster (8 GeV)
  - Collider ring
- **IP/detectors**
  - Two, full acceptance
  - Hori. crab crossing
- **Polarization**
  - Figure-8 shape

Design Report



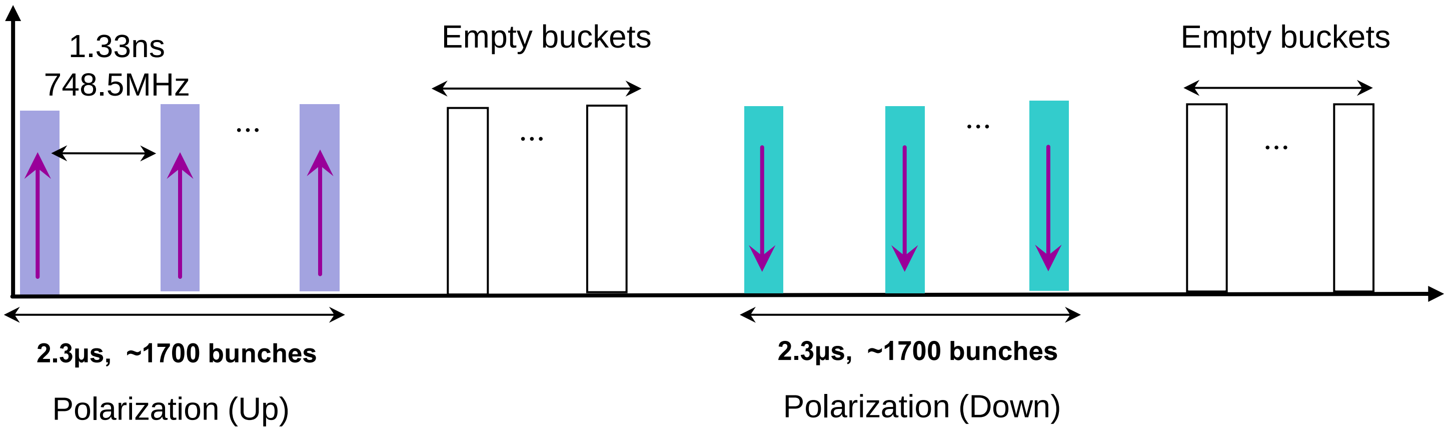


JLEIC Baseline New Parameters

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emitt., hor./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam param.		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	2.5		21.4		5.9	

Bunch Structure In Collider Ring

bunch train & polarization pattern in the collider ring

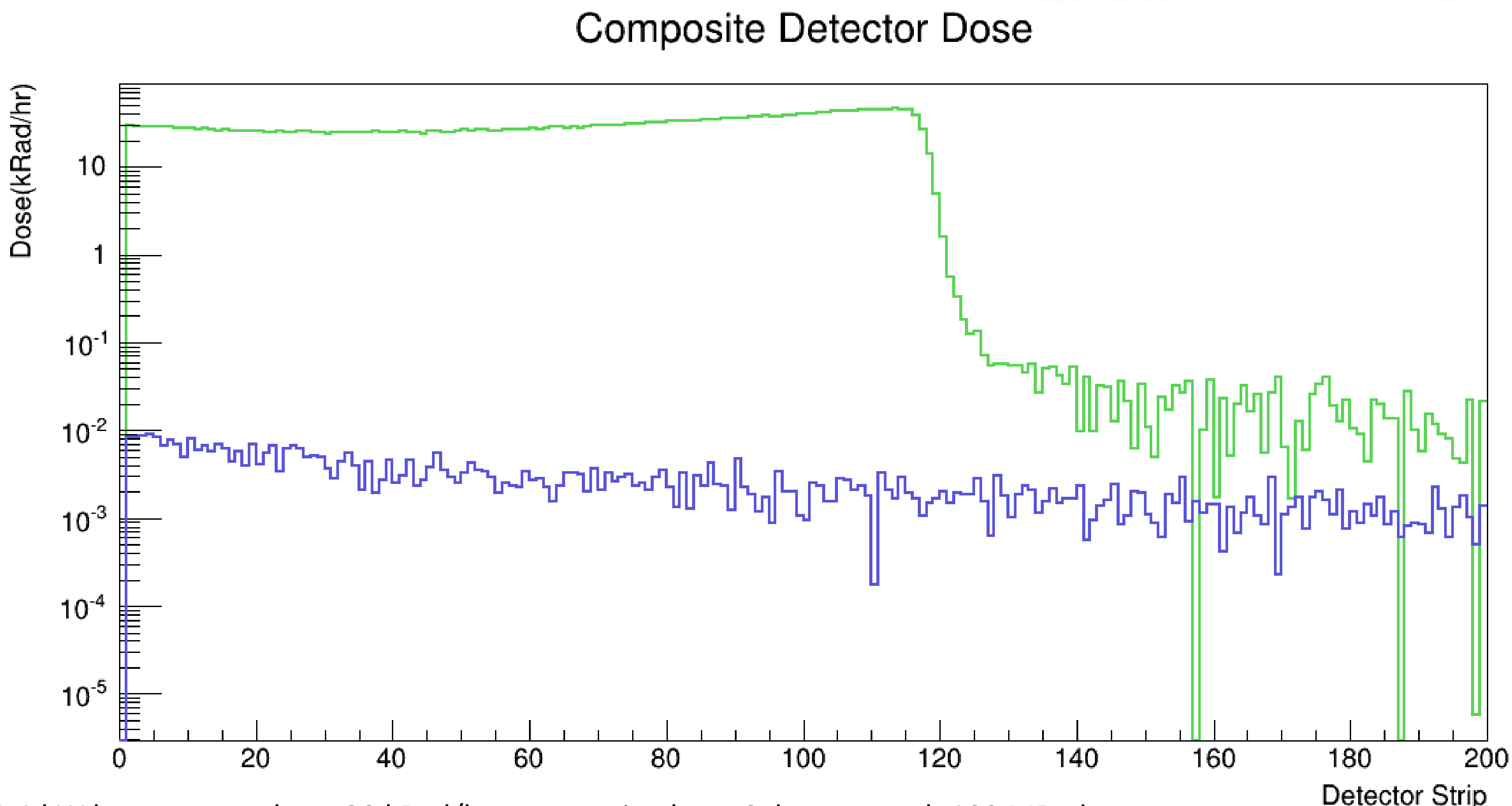


Measurement times for 1% statistics

Energy	Current	1 pass laser (10 W)		FP cavity (1kW)	
(GeV)	(A)	Rate (MHz)	Time for 1% uncertainty (ms)	Rate (MHz)	Time for 1% uncertainty (ms)
3	3	26.8	161	310	14
5	3	16.4	106	188	9
10	0.72	1.8	312	21	27

Typical measurement takes less than 1 second even at 10 Watts of laser power
1320 bunches in eRHIC , 2x1700 bunches in JLEIC
High laser power required, need to measure all bunches
Time scale from 4.5 to 8.6 hours at 10 kW

Radiation hardness



1 A 1 kW laser power about 30 kRad/hour per strip about 6 days to reach 100 MRad
Consistent with estimation from a previous experiment in Hall C which showed no damages for the diamond detector after 10 MRad regular silicon looses 50 % of amplitude after 10 MRad
Operate diamond detector at low duty cycle (1s/10 min) and lower laser power (10 W) to extend lifetime up to few years : Radiation hard detector allows continuous monitoring of the polarization

Requirements

- Need to be able to separate two bunches to avoid
  - detector and electronic response faster than bunch frequency
- Radiation hardness because of signal and background

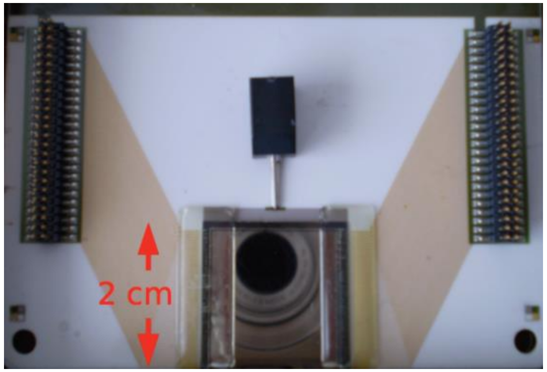
Compton polarimeter electron detector

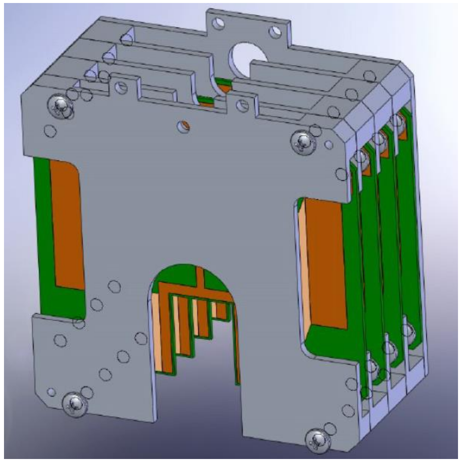
- Detector options (rough properties)

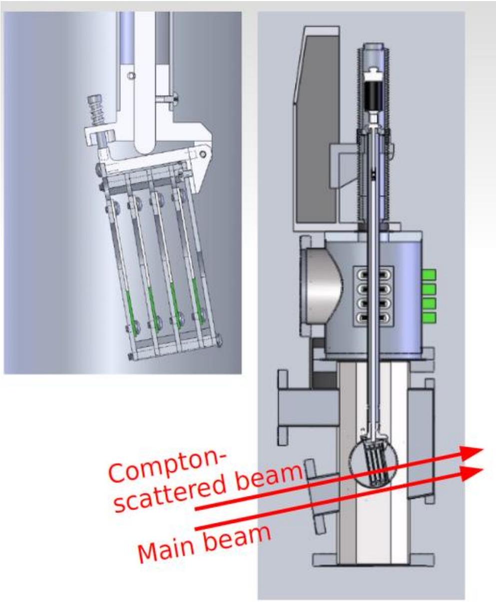
Detector	si	LGAD	Diamond	MAPS	Superconducting
Thickness	200 um	50 to 30 um	500 um	50 to 30 um	50 to 30 um
Neutron fluence	3.10^15	3.10^16	10^16	>5.10^14	?
Dose Mrad	3	30	100	1	?
Timing resolution	50 ns	30 ps	80 ps	<16 ns	10 ps
Costs	$	$	$$$	$	$$$$ (cryo)

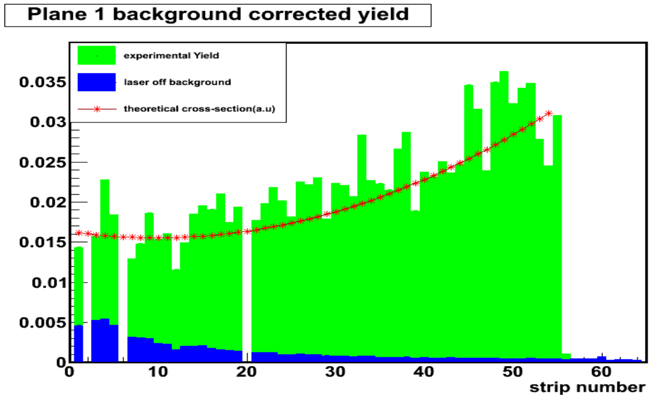
Compton polarimeter electron detector

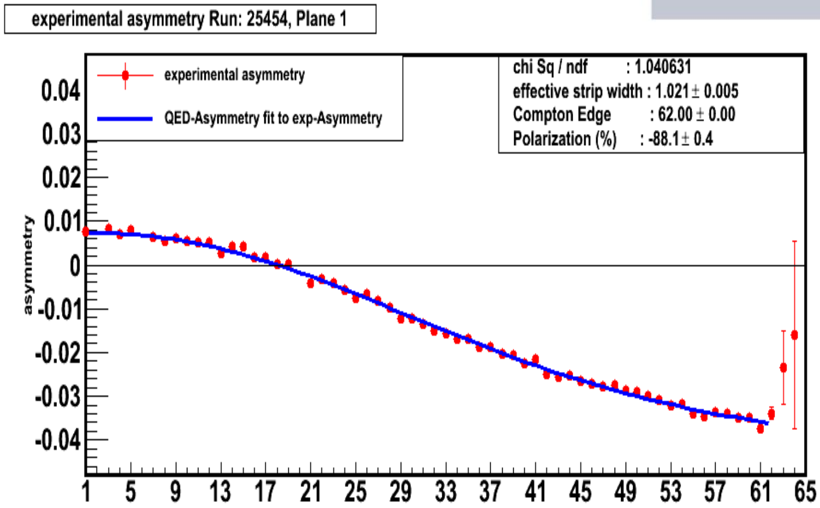
- Silicon or diamond strip option
- About 200 to 250 strips
  250 μm width
- 5 cm length to catch zero crossing





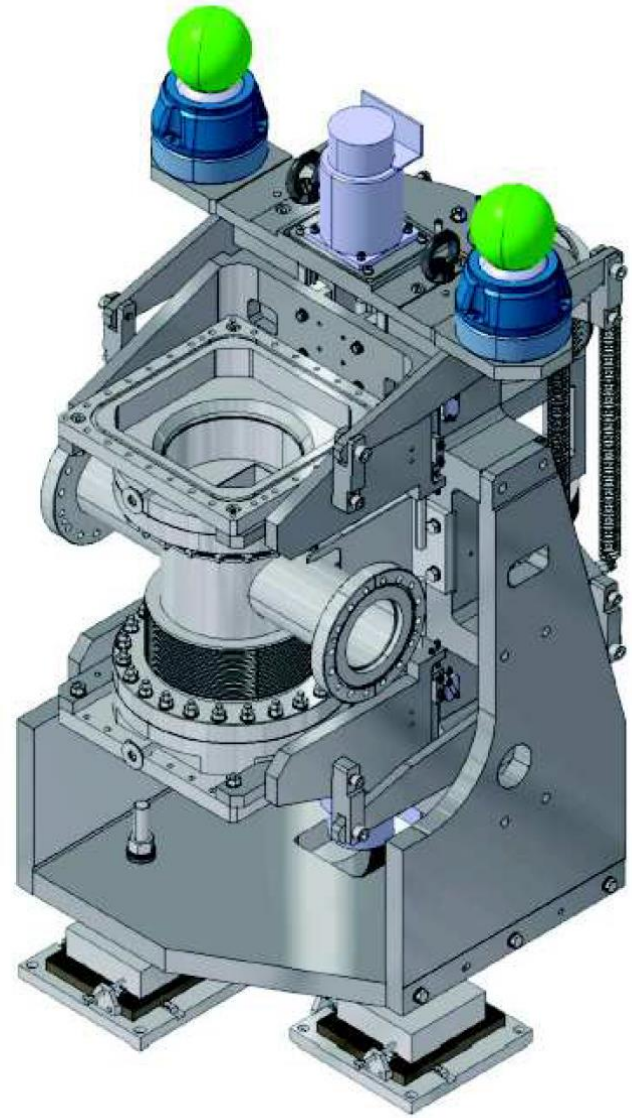




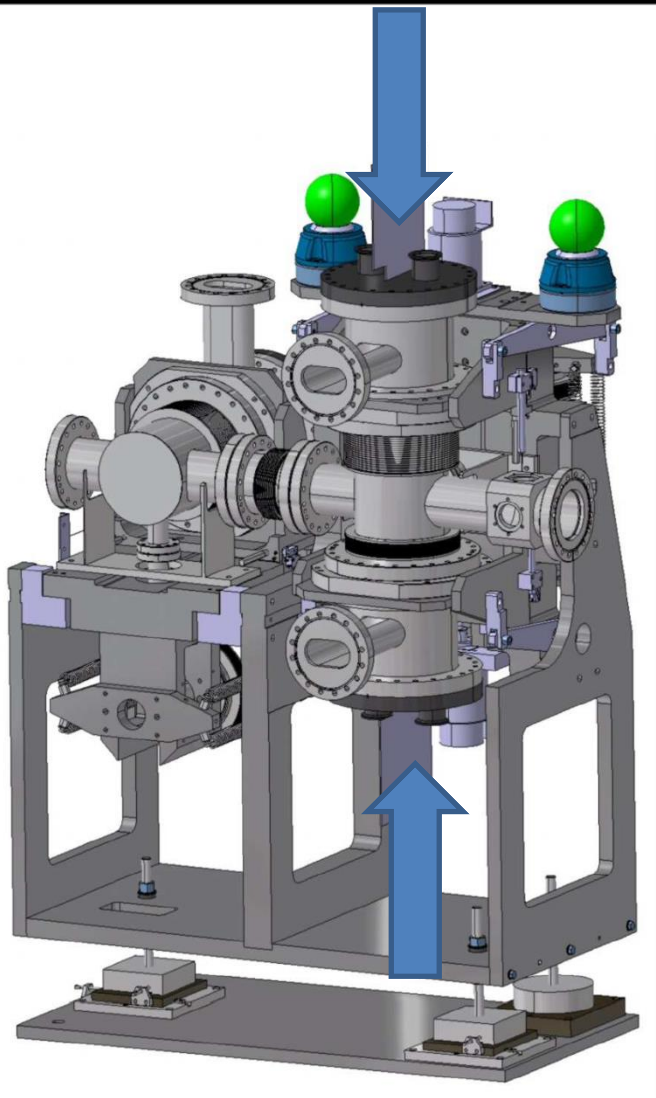


Roman pots from TOTEM

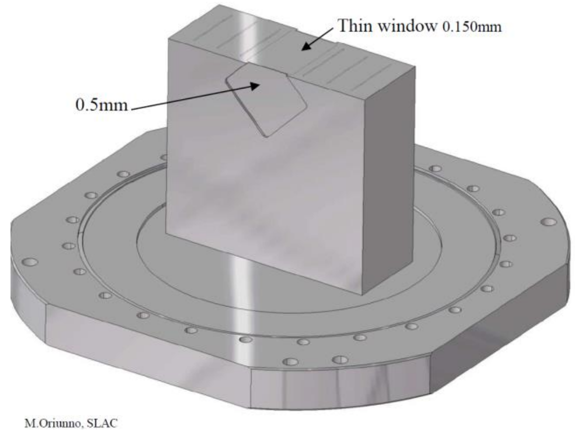
- For small angle detection
- Two chambers
- Thin window
- Can be moved in and out from beam
- Typical 10 to 15 sigma
- Up to 4-5 sigma in optimal places
- Might work for electron side at both JLEIC and eRHIC to be studied

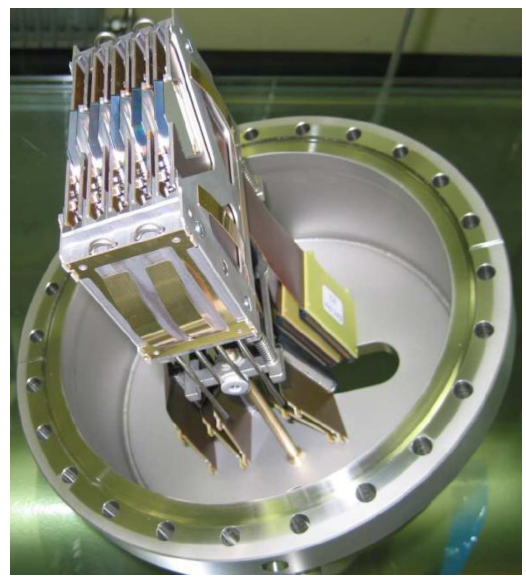


Example TOTEM RP

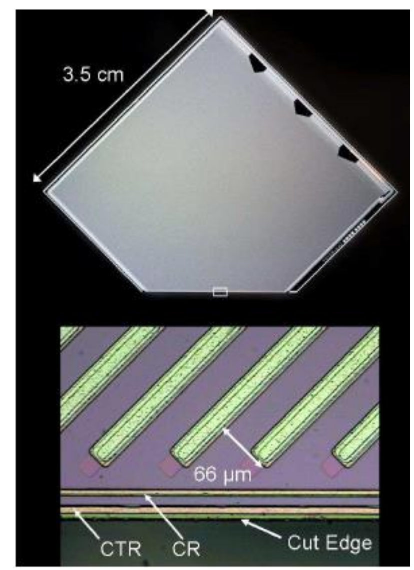


Marco Oriunno SLAC





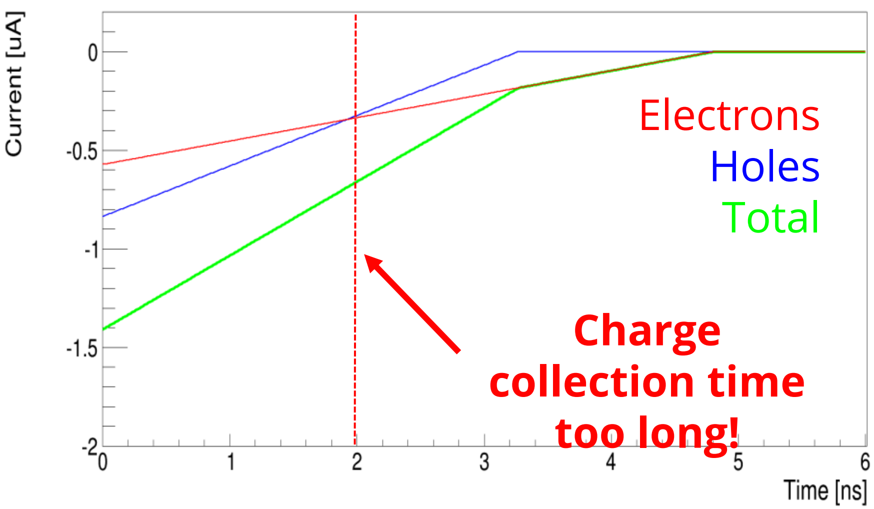
- secondary chamber which can be moved in and out from the beam
- several planes of solid state detector (silicon, diamond, LGAD)



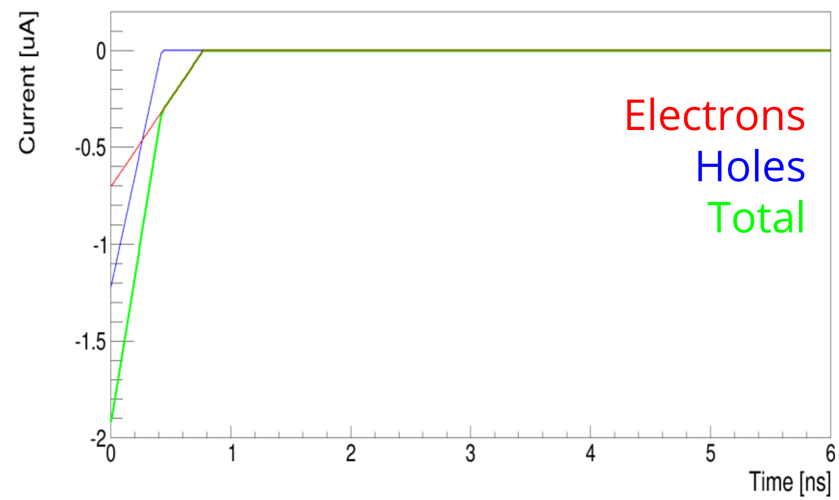
Is it possible to design a MIP detector with a signal shorter than 2 ns?

Diamond sensors are among the fastest available

Nicola Minafra



500 µm scCVD diamond @ 800V



80 µm scCVD diamond @ 500V

The collection time t_c depends on the thickness d $\quad t_c \sim {}^{d}/_{v_s}$

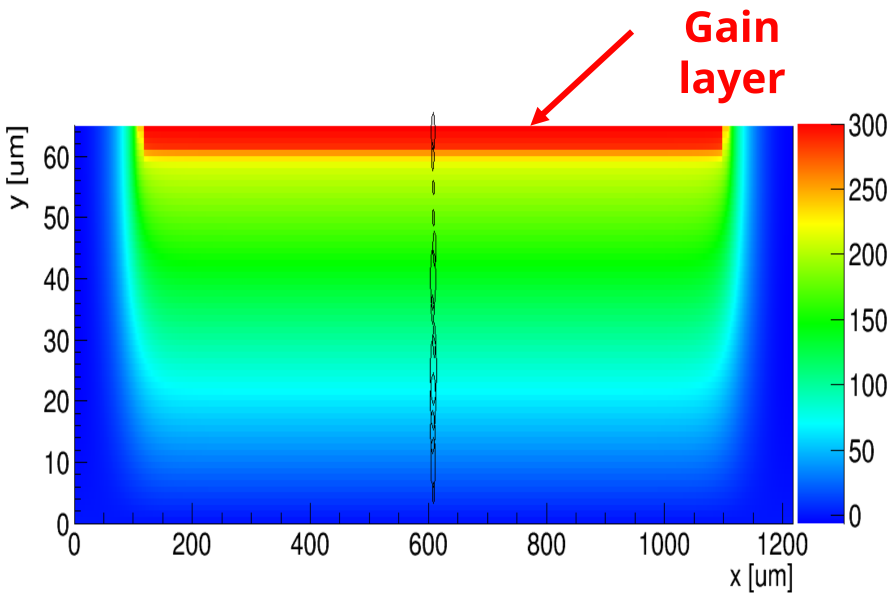
NOTE: the collected charge $Q_c = \int i\,(t)\,dt$ also depends on the thickness d
$Q_c \sim d$

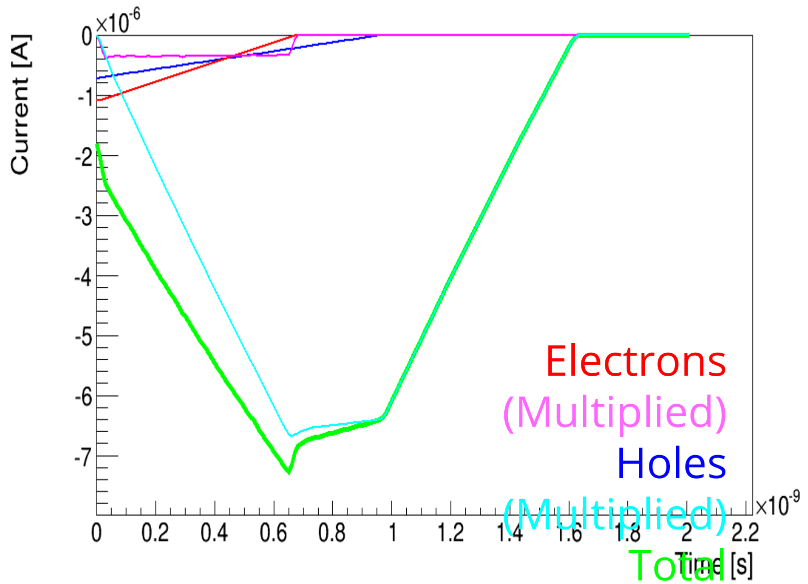
However, the deep current mainly depends on the carriers' velocities, i.e. electric field $\quad |i_{max}| \sim {}^{Q_c}/$

Is it possible to design a MIP detector with a signal shorter than 2 ns?

Ultra Fast Silicon Detectors: as fast as diamond, but with a gain layer!

Nicola Minafra





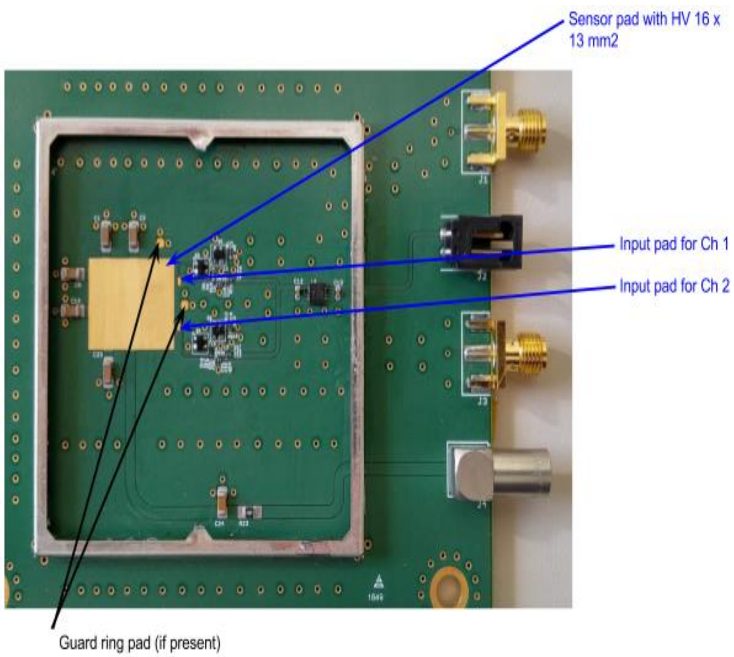
UFSD: 50 μm LGAD

Fast collection time (50 μm thick) and larger signals, thanks to the gain layer

Electronics for very fast detectors

Nicola Minafra

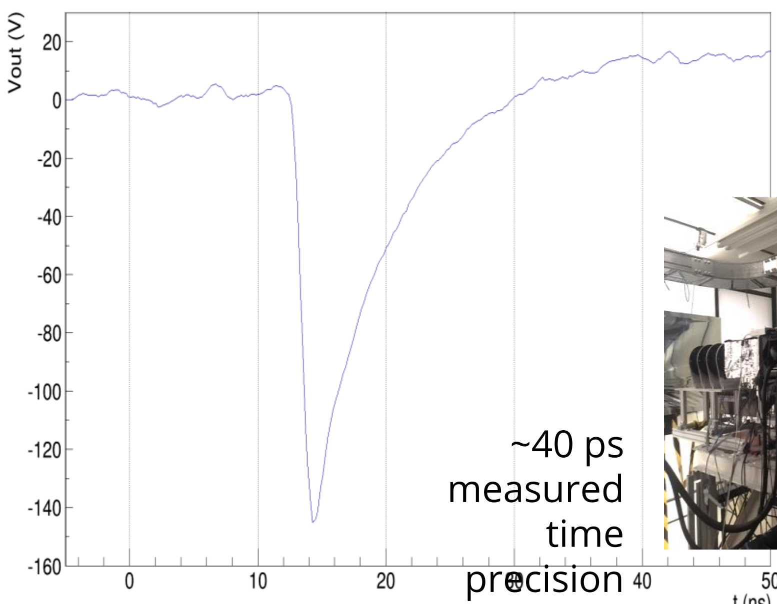
A two channels board was designed and manufactured for the characterization of different solid state detectors.



Sensors up to 16x13 mm^2 can be glued and bonded.

The components can be easily adapted to accommodate:

- Diamond sensors: ~1 nA bias current, both polarities, small signal
- Silicon seonsors: ~100 nA bias current, small signal
- UFSD ~100 nA bias current, ~ larger signal
- SiPM: ~ 5 uA bias current, large signal



3x3 mm^2 UFSD MIP beam test @

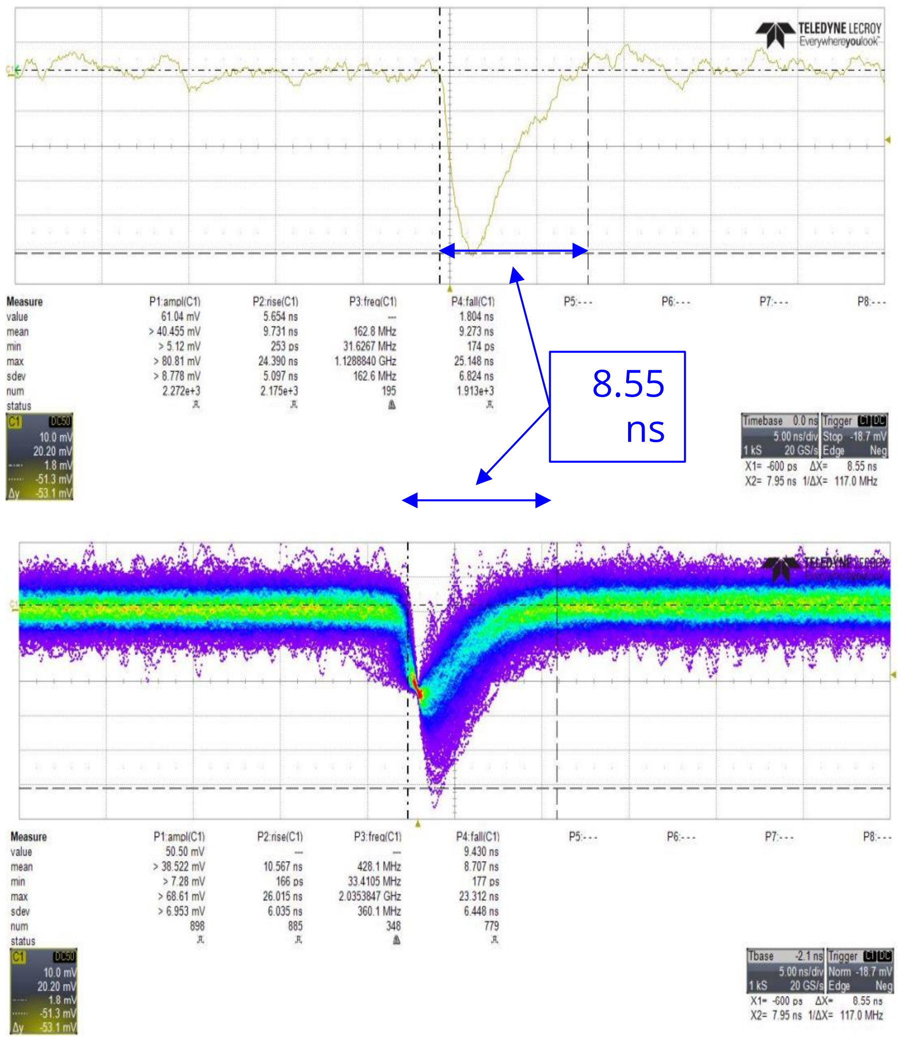
~40 ps measured time precision

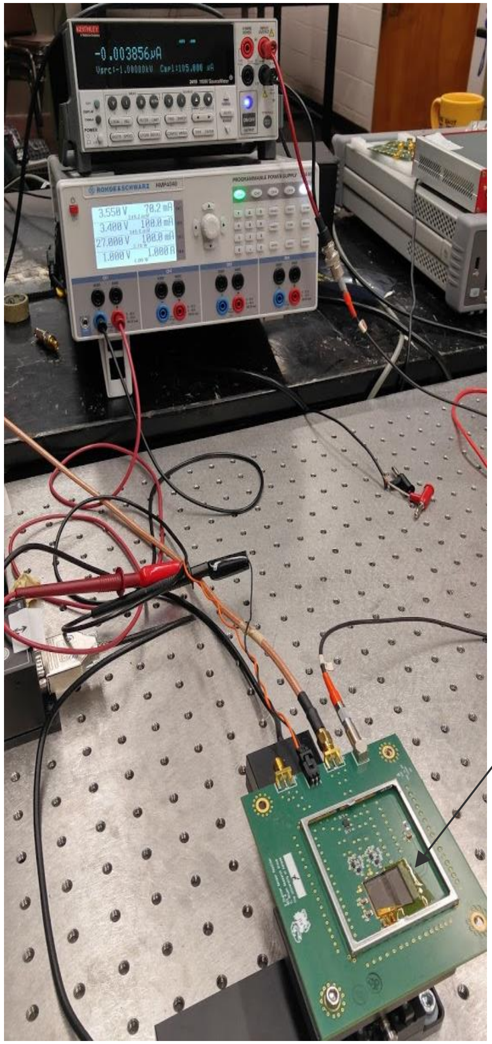
The board was optimized to achieve a good time precision with different sensors, however it can be modified to have an output signal shorter (but less precise)

[Test of Ultra Fast Silicon Detectors for Picosecond Time Measurements with a New Multipurpose Read-Out Board]

Electronics for very fast detectors

This board was also used to test the performance of a diamond sensor using a Sr^{90} β^- source.





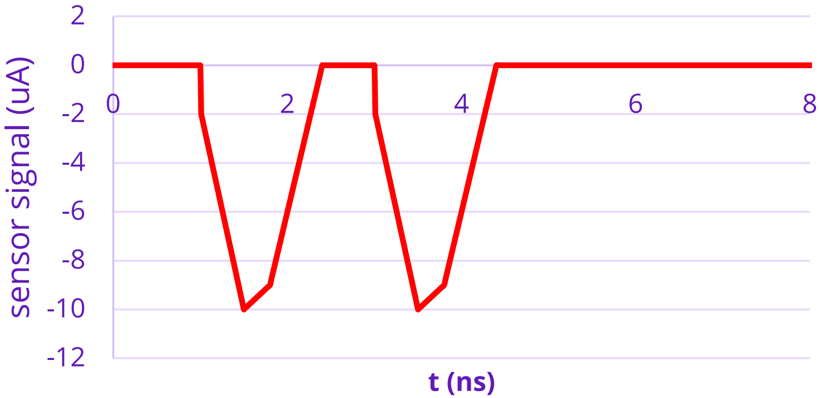
500 µm pcCVD diamond

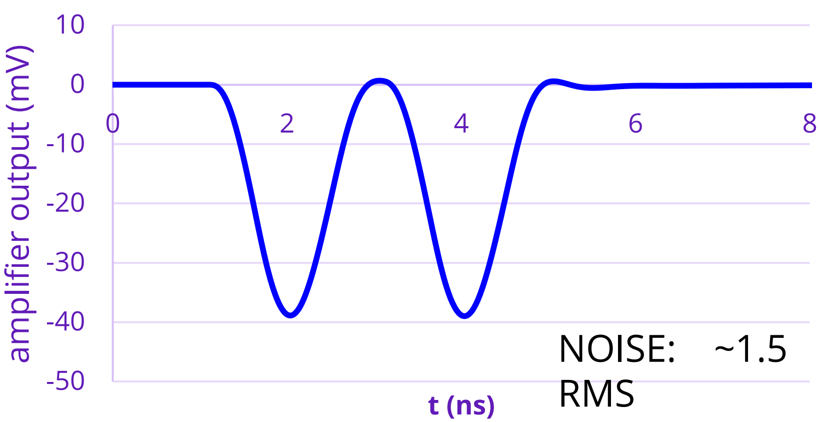
Is it possible to design a MIP detector with a signal shorter than 2 ns?

Nicola Minafra

Simulated results:

UFSD

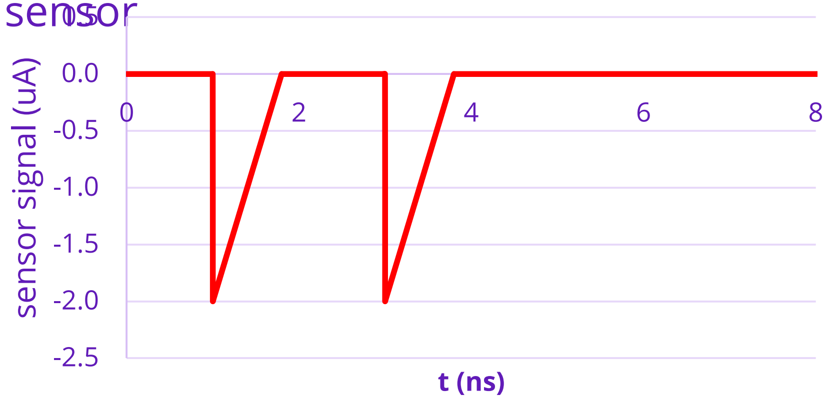


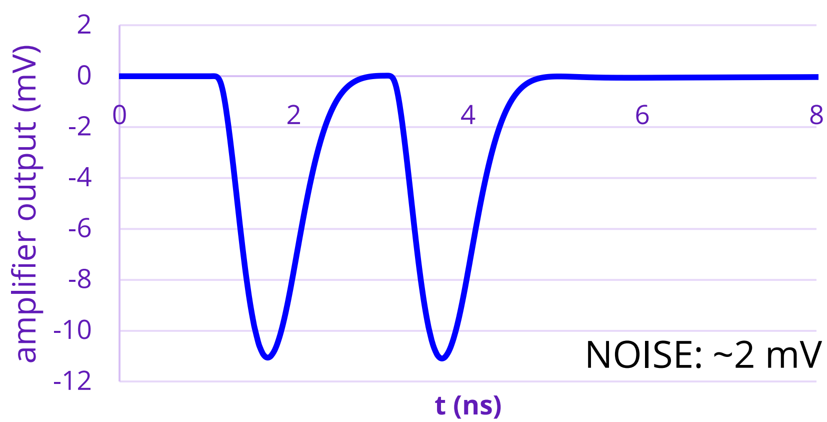


NOISE: ~1.5 mV RMS

SNR ~ 25

80 µm scCVD diamond sensor



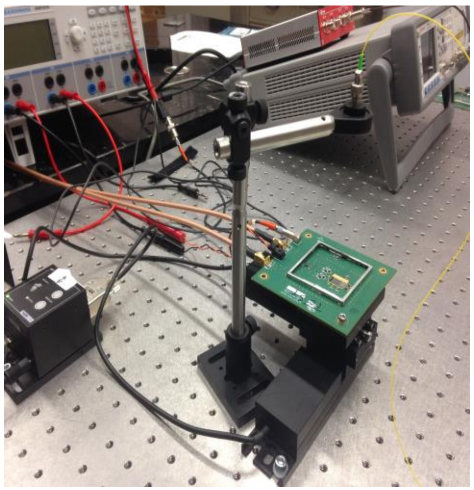


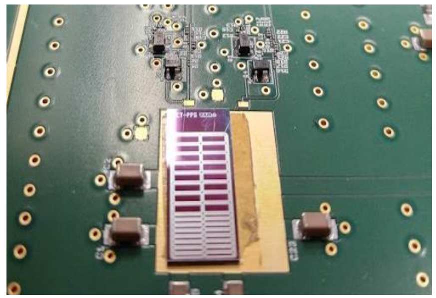
NOISE: ~2 mV RMS

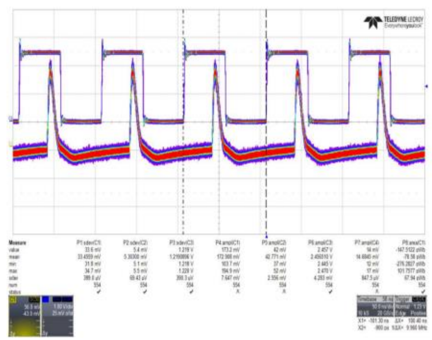
SNR ~ 5

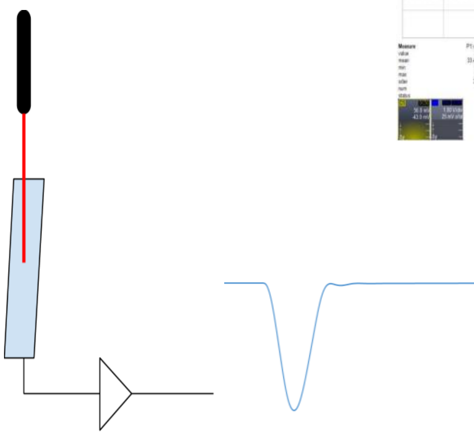
Laser tests for silicon sensors

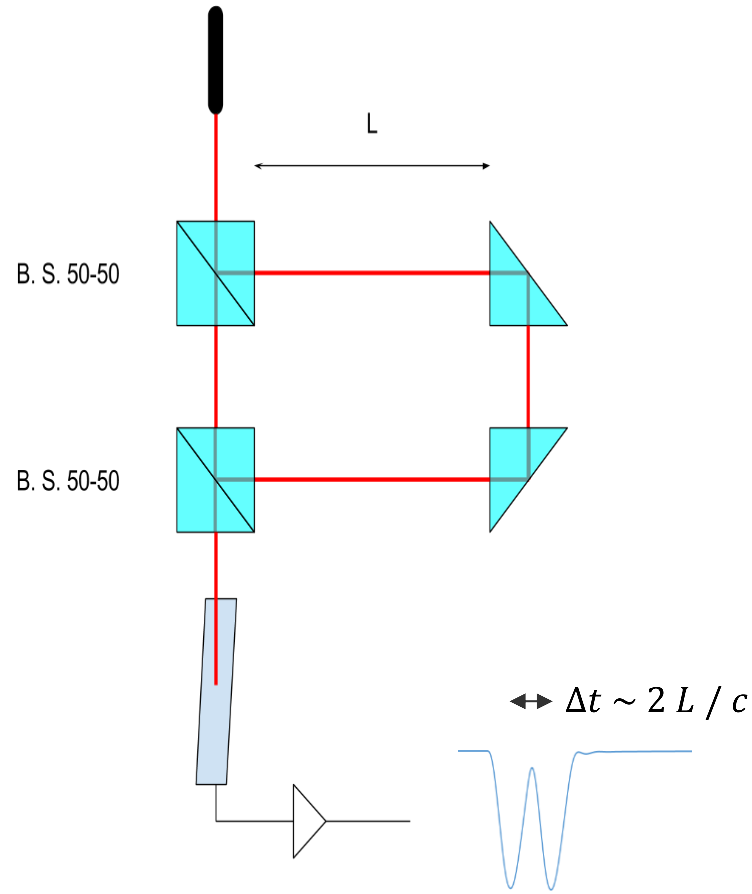
To test the high rate capabilities of the detector a laser pulse can be used







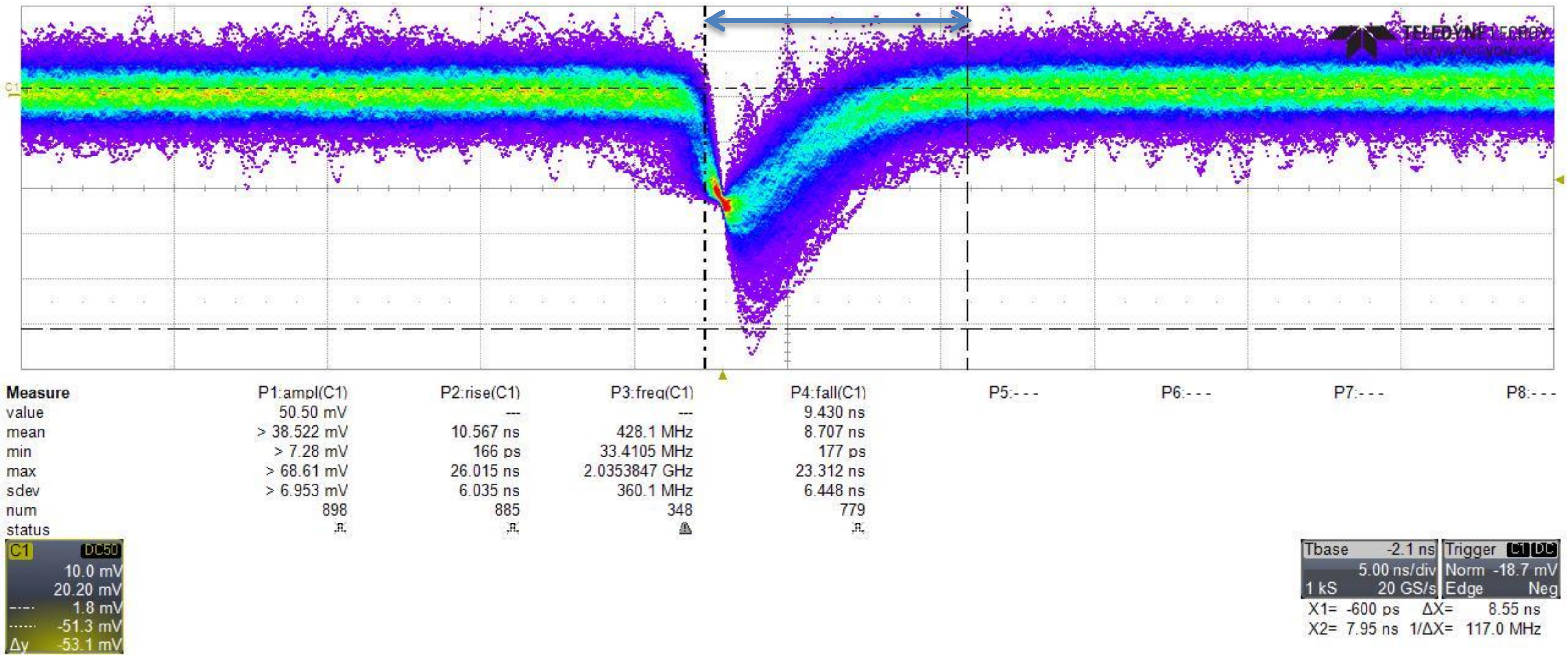




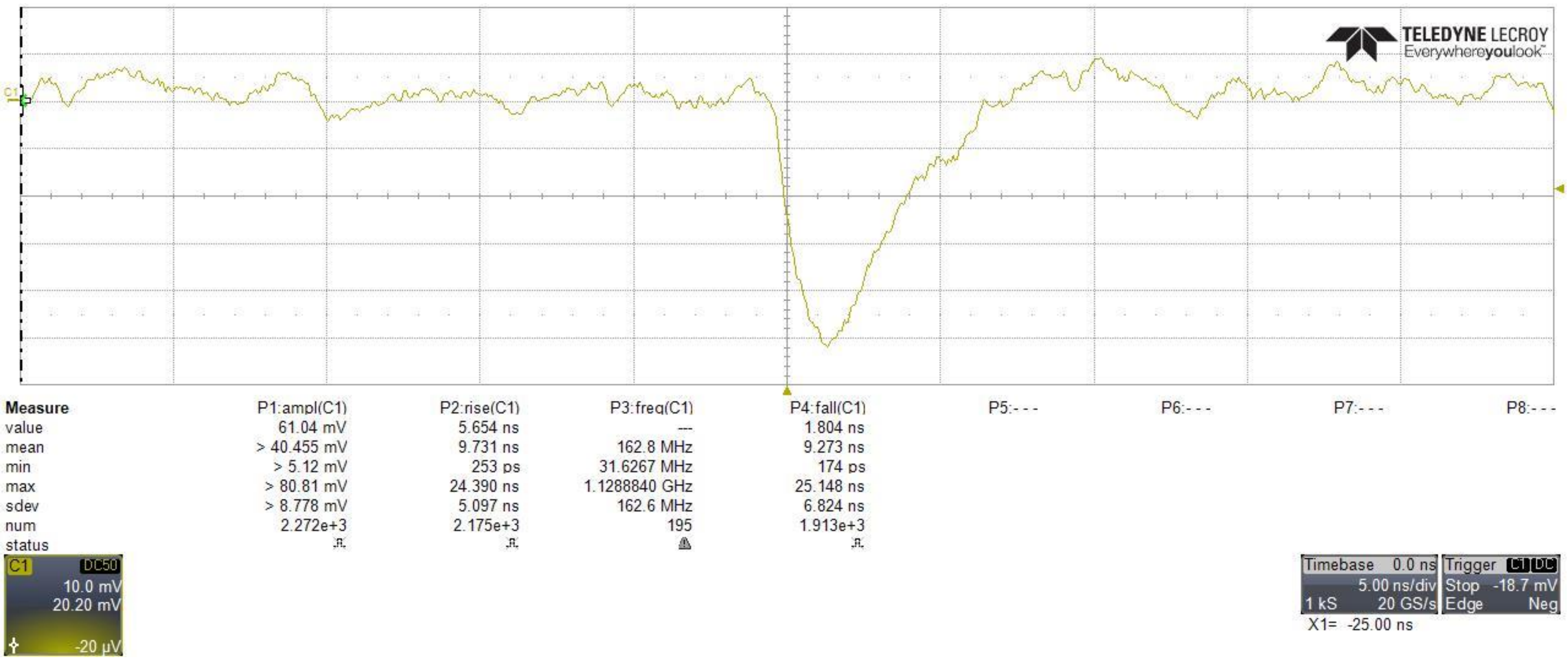
1080 nm picosecond laser, 50 ps wide pulses with peak power > 100 mW set at 10 cm away from the sensor board.
The support can be moved XY with micrometric accuracy

Diamond with amplifier

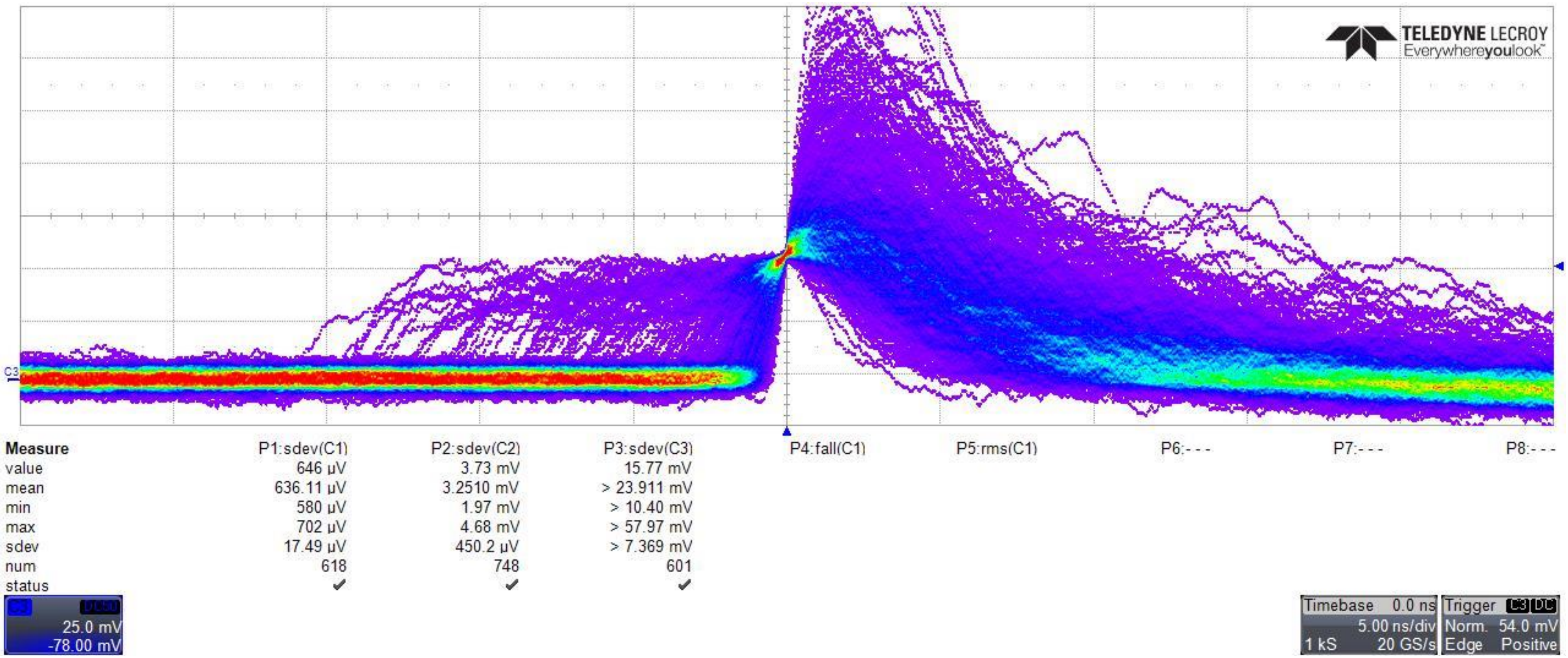
8.55 ns



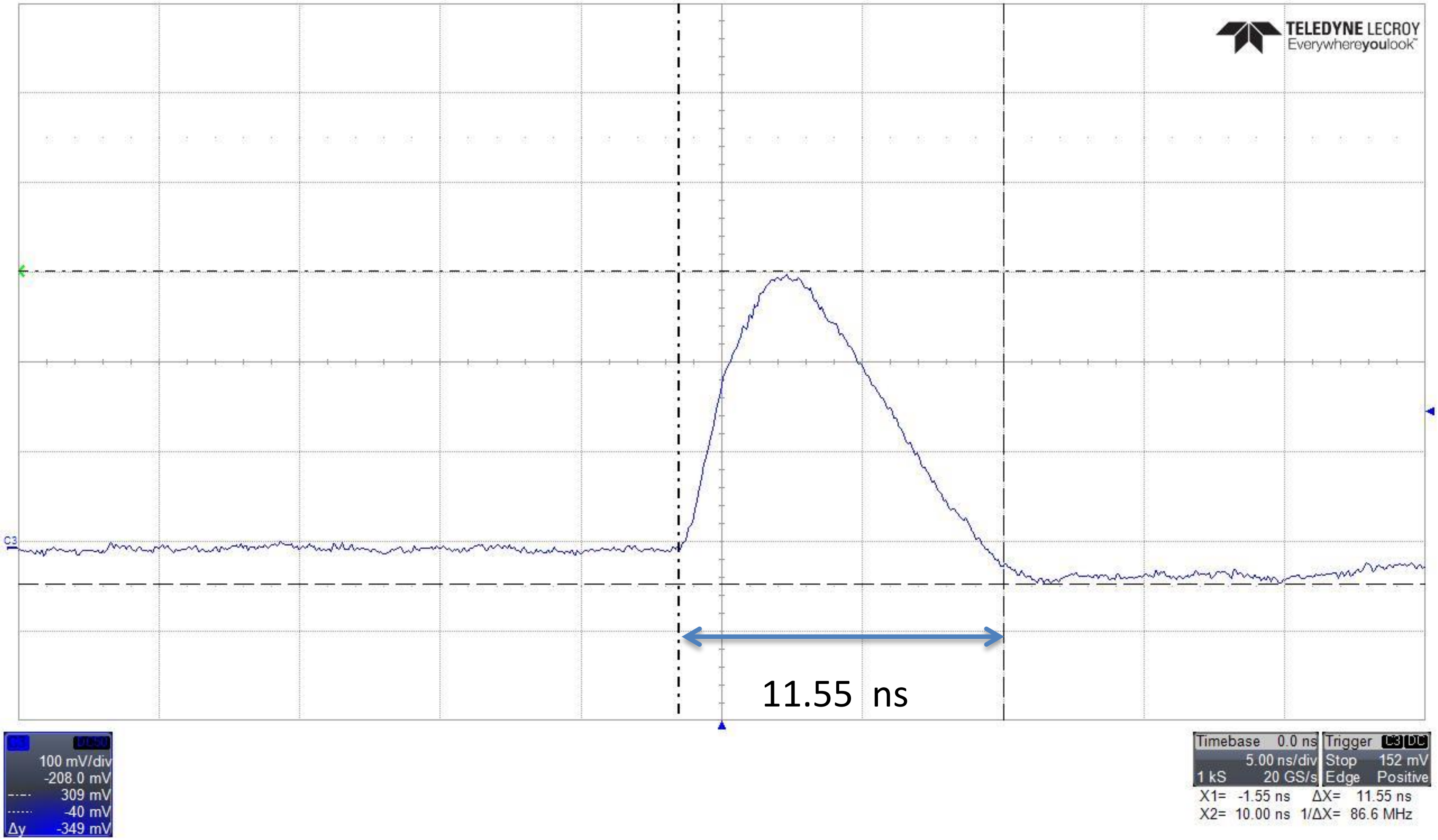
Diamond pulse



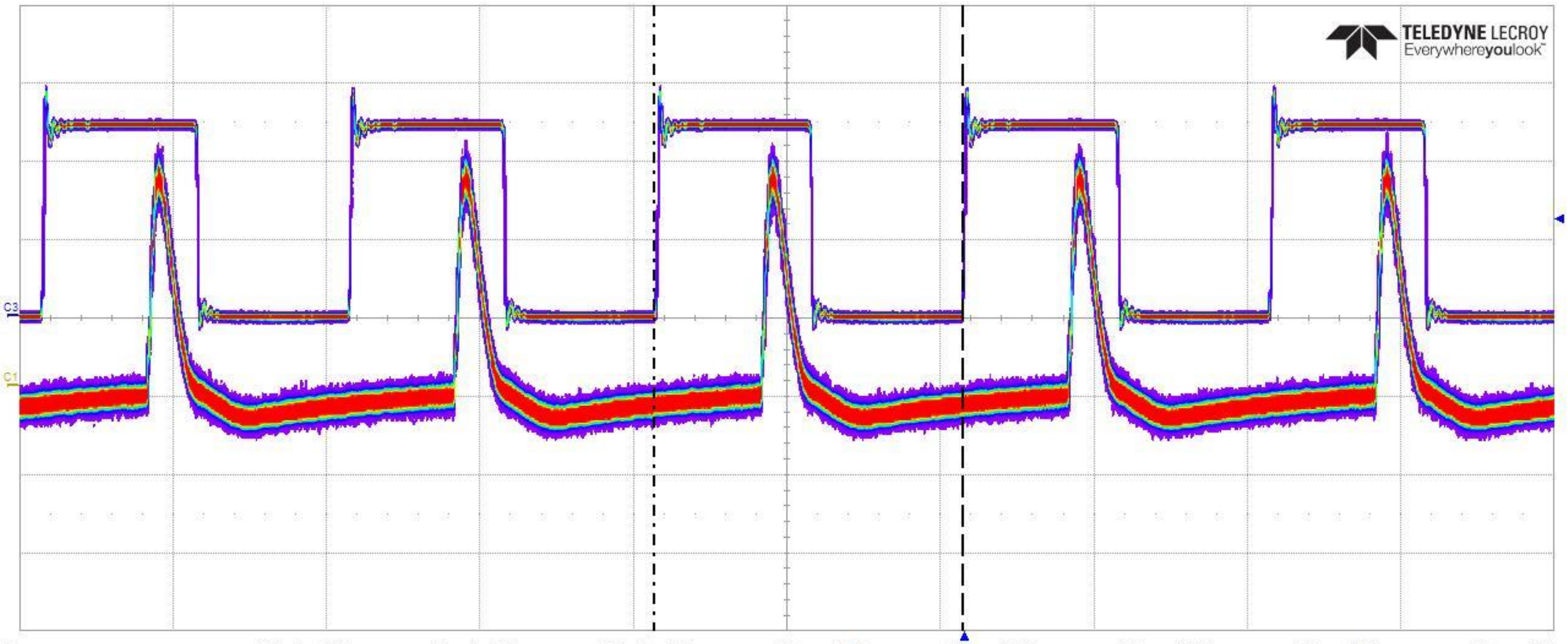
Silicon


TELEDYNE LECROY
Everywhereyoulook
C3
Measure
P1:sdev(C1)
P2:sdev(C2)
P3:sdev(C3)
P4:fall(C1)
P5:rms(C1)
P6:- - -
P7:- - -
P8:- - -
value 646 µV 3.73 mV 15.77 mV
mean 636.11 µV 3.2510 mV > 23.911 mV
min 580 µV 1.97 mV > 10.40 mV
max 702 µV 4.68 mV > 57.97 mV
sdev 17.49 µV 450.2 µV > 7.369 mV
num 618 748 601
status
25.0 mV
-78.00 mV
Timebase 0.0 ns
5.00 ns/div
1 kS 20 GS/s
Trigger
Norm. 54.0 mV
Edge Positive

Silicon single pulse



Silicon 10 MHz laser



Measure	P1:sdev(C1)	P2:sdev(C2)	P3:sdev(C3)	P4:ampl(C1)	P5:ampl(C2)	P6:ampl(C3)	P7:ampl(C4)	P8:area(C1)
value	33.6 mV	5.4 mV	1.219 V	173.2 mV	42 mV	2.457 V	14 mV	-147.5122 pWb
mean	33.4559 mV	5.30300 mV	1.2190896 V	172.908 mV	42.771 mV	2.456510 V	14.6845 mV	-78.58 pWb
min	31.8 mV	5.1 mV	1.218 V	103.7 mV	37 mV	2.445 V	12 mV	-276.2827 pWb
max	34.7 mV	5.5 mV	1.220 V	194.9 mV	52 mV	2.470 V	17 mV	101.7577 pWb
sdev	389.0 µV	69.43 µV	390.3 µV	7.647 mV	2.556 mV	4.283 mV	847.5 µV	67.94 pWb
num	554	554	554	554	554	554	554	554
status	✓	✓	✓	⎍	⎍	✓	⎍	✓

C1 DC50
50.0 mV
-43.0 mV

C3 BwL DC50
1.00 V/div
25 mV ofst

Timebase 58 ns
50.0 ns/div
10 kS 20 GS/s

Trigger C3 DC
Normal 1.23 V
Edge Positive

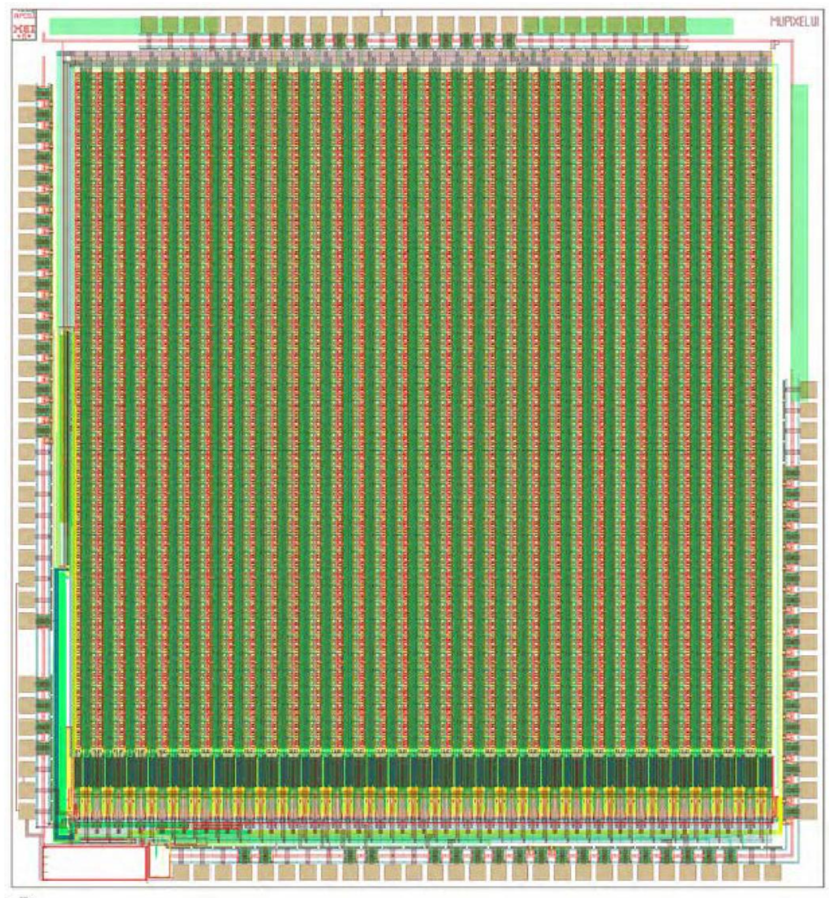
X1= -101.30 ns ΔX= 100.40 ns
X2= -900 ps 1/ΔX= 9.960 MHz

MAPS option

HVMAPS as Compton e-Detectors

MuPix 10 HVMAPS:

Full chip 2x2 cm^2:



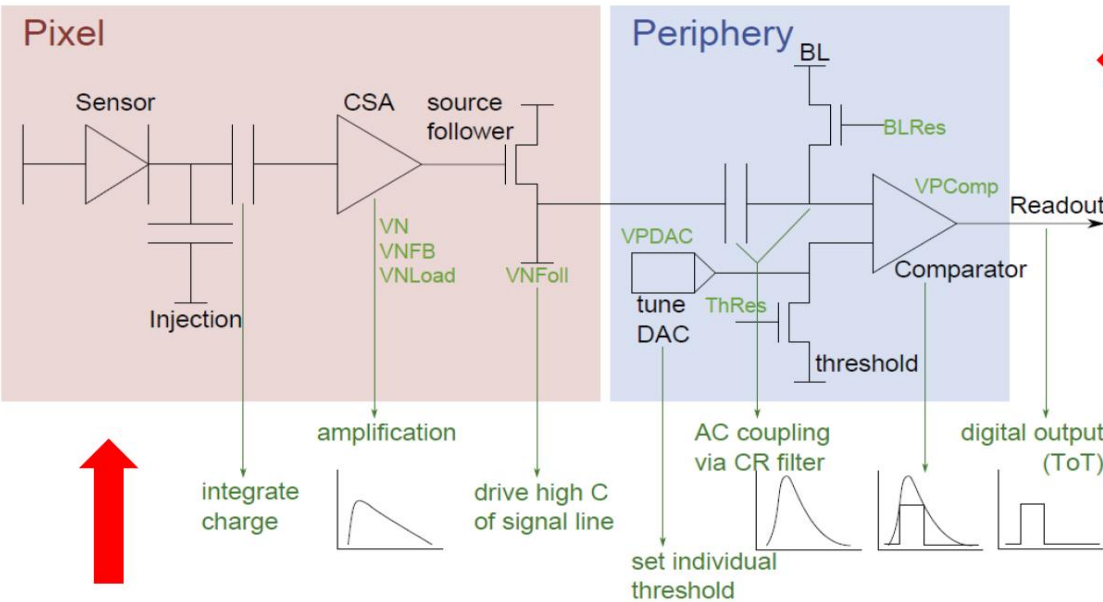
Option for 12 GeV Moller experiment

Started procuring for testing

HVMAPS as Compton e-Detectors

HVMAPS Design:

In-Pixel and periphery electronics:



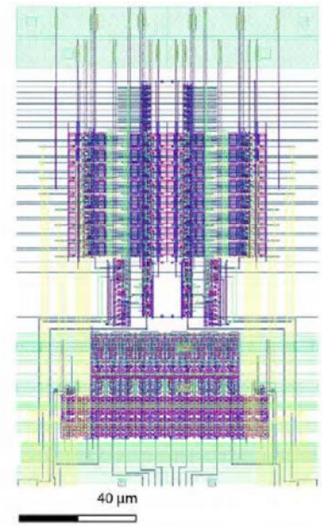
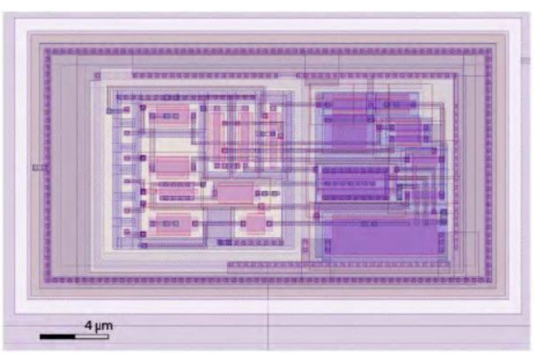


Figure 7.10: Layout of the double end of column in the MuPix 7.

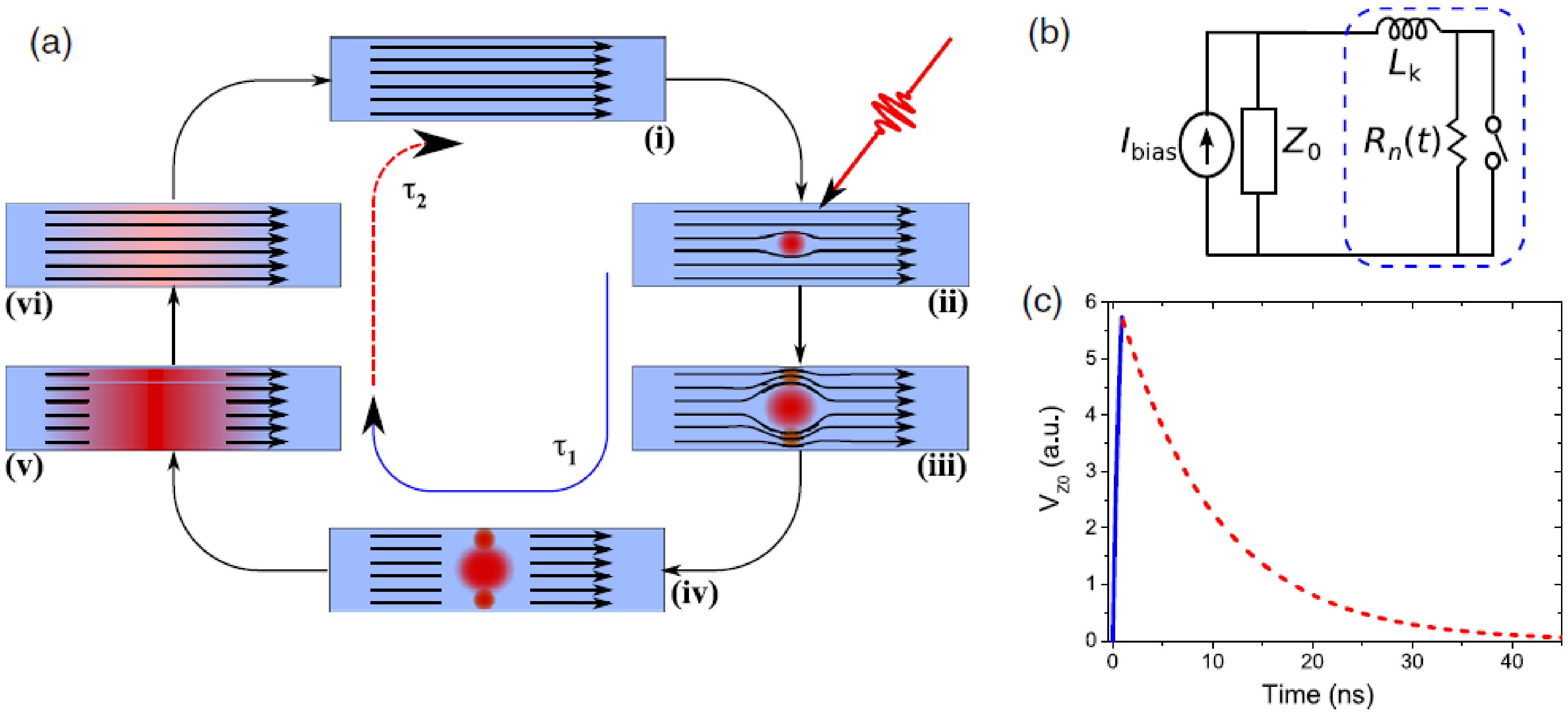


Superconducting detectors

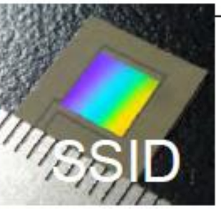
	Two spectroscopic domains		
Type	Energy	Time	Temp.
Calorimeter TES, MMC…	Extremely high(1.2 eV)	Slow (ms)	< 0.1 K
STJ	High (3 - 6 eV)	Fast (μs)	0.3 K
SSD (nano-strip)	N/A	Extremely fast (< 1 ns)	> 4.2 K

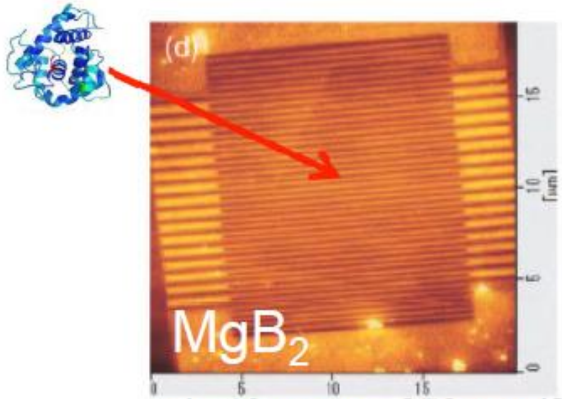
Single Superconducting Nanowire Photon Detectors (SNSPD)

- Review : Chandra M Natarajan *et al* 2012 *Supercond. Sci. Technol.* **25** 063001 [doi:10.1088/0953-2048/25/6/063001](doi:10.1088/0953-2048/25/6/063001)

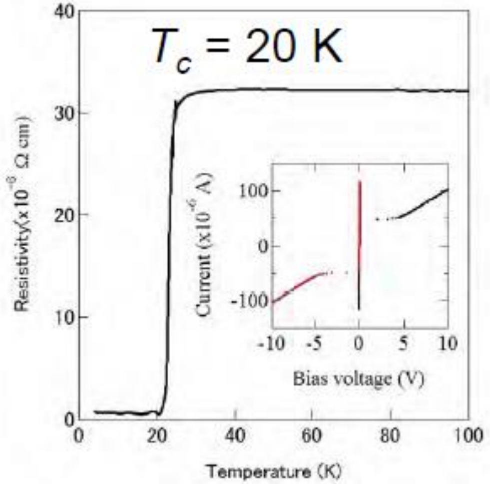


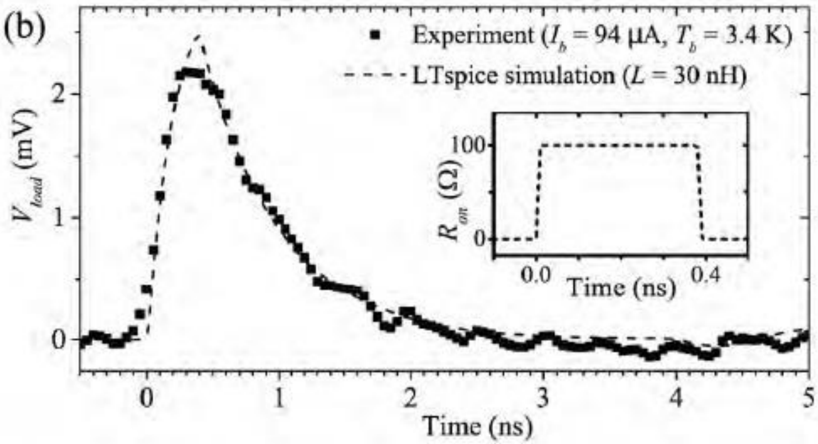
Detection of lysozyme ions with MgB_2-SSID

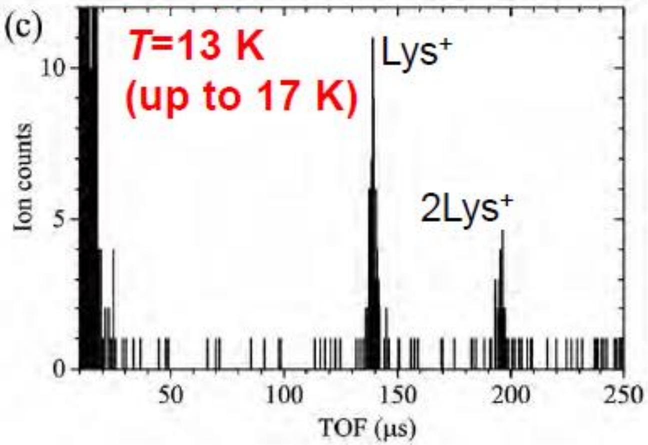




d =10 nm, w=250 nm (2 nm-AlN)
10×10 μm², I_c = 96 A







LTspice can reproduce the pulse shape.

Mass spectrum was obtained.

N. Zen, *et al.*, *Appl. Phys. Lett.* **106**, 222601 (2015).

Features of SNSPD

Pro

- Very good timing resolution
- Very small : very good position resolution
- No energy information
- likely radiation hard

Cons

- Cryogenics
- Photon detector only (could use Cerenkov radiator), MIP detector to be designed and demonstrated

Conclusion

– existing detector and electronics can separate 10 ns spaced pulsed
– some R&D required for 2 ns bunch spacing but seems doable for diamond, other technologies to be studied mostly question of costs
– radiation hardness needs to be taken into account
– MAPS, LGAD most likely to work but might need frequent more frequent change of detector
– Superconducting detectors ruled out because of cryogenics requirement